UC BERKELEY SOLAR VEHICLE TEAM

Gen XI Steering + Stability

Critical Design Review

Menooa Avrand

July 11, 2025

Stability Design Overview

UC BERKELEY SOLAR VEHICLE TEAM

CALSOL
UC BERKELEY SOLAR VEHICLE TEAM

Stability Functional Requirements + Constraints

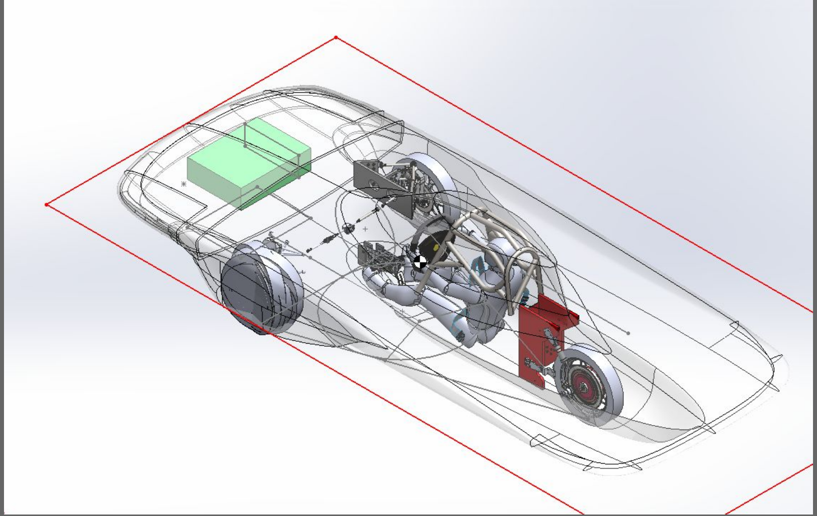
- Determine vehicle dimensions + large mass item locations
  - Ensure no tipping if car tilted at 45 degrees w.r.t axis made w/ any two wheels
  - 104mm ground clearance (Regs @ 100mm)
  - Fit in trailer
  - Wheel angles < 25 degrees maintaining 7.5m turning radius

Design Details

- Input all mass heavy items are respective locations based on subteam values
  - Took inspiration from excalibur and impulse on manufacturing mass errors and location functionality

Full list of items + values

- roll cage - driver - pedal mount - seat belt
- steering wheel battery - electrical - array
- rims + tires, motor, suspension



UC BERKELEY SOLAR VEHICLE TEAM

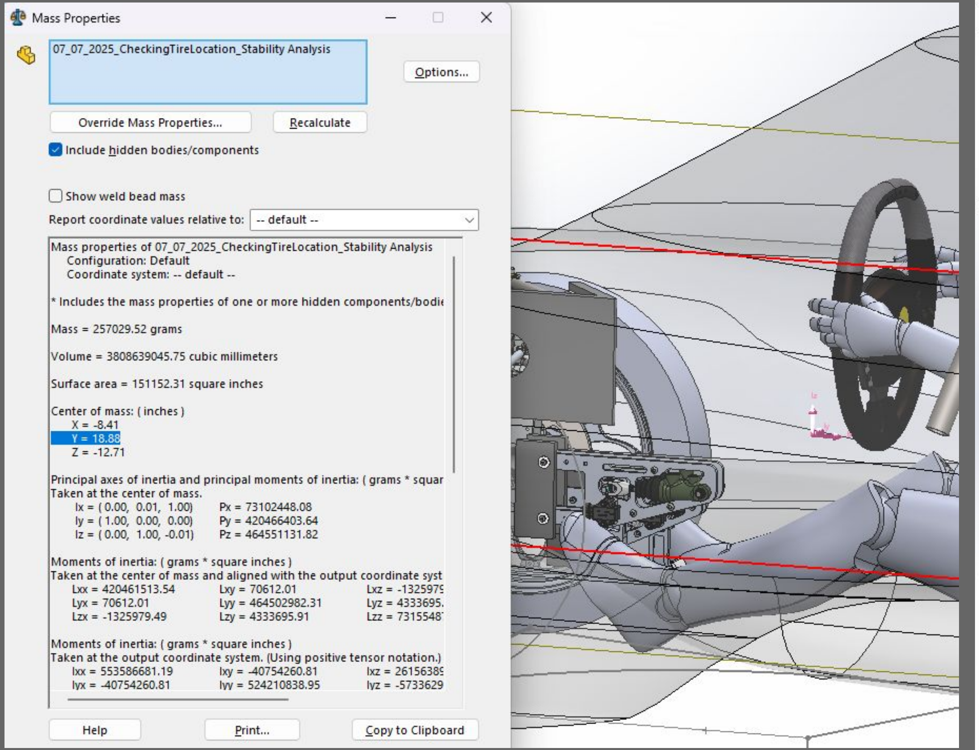
Design Details - Tipping Condition Satisfaction pt 1

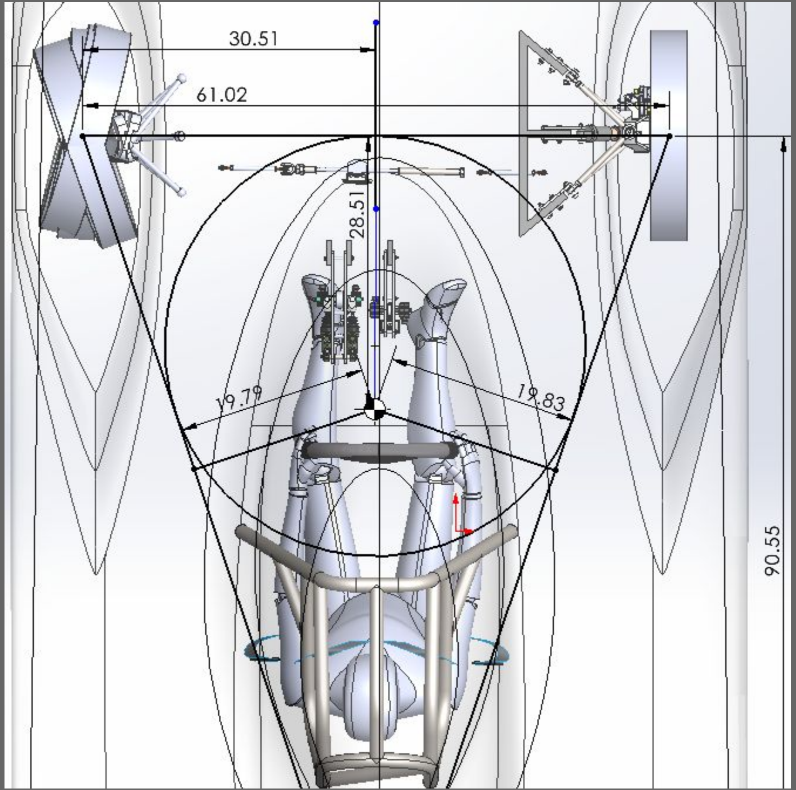
- Pass Tipping Condition
  - actual COG < distance between COG and axis made w.r.t any two wheels
  - actual COG < geometrical max COG

- 1. Maximum COG location based on vehicle dimensions
  - Calculator made by Jae Won & Maddy from old trade study allows us to obtain max allowable COG z-height for any vehicle dimension
  - For 1.55m TW – 2.3m WB
    - 21.92 inches max allowable COG z-height

CALSOL
UC BERKELEY SOLAR VEHICLE TEAM

Design Details - Tipping Condition Satisfaction pt 2





CALSOL
UC BERKELEY SOLAR VEHICLE TEAM

Design Details - Tipping Condition Satisfaction pt 3

- Actual Z-height 18.88 in < Geometric Max of 21.92 in ✓
- Distance from COG to line made w.r.t any two wheels ✓
  - 19.79in | 19.83in | 28.51in
  - Our actual Z-height is smaller than these distances, signifying tipping condition met
- Room for z-height error of 0.91inches
  - This may seem small but it is quite difficult to shift the COG vertically
    - Notes: Roll cage and top shell have the most influence to affect this negatively

Steering Design Overview

UC BERKELEY SOLAR VEHICLE TEAM

UC BERKELEY SOLAR VEHICLE TEAM

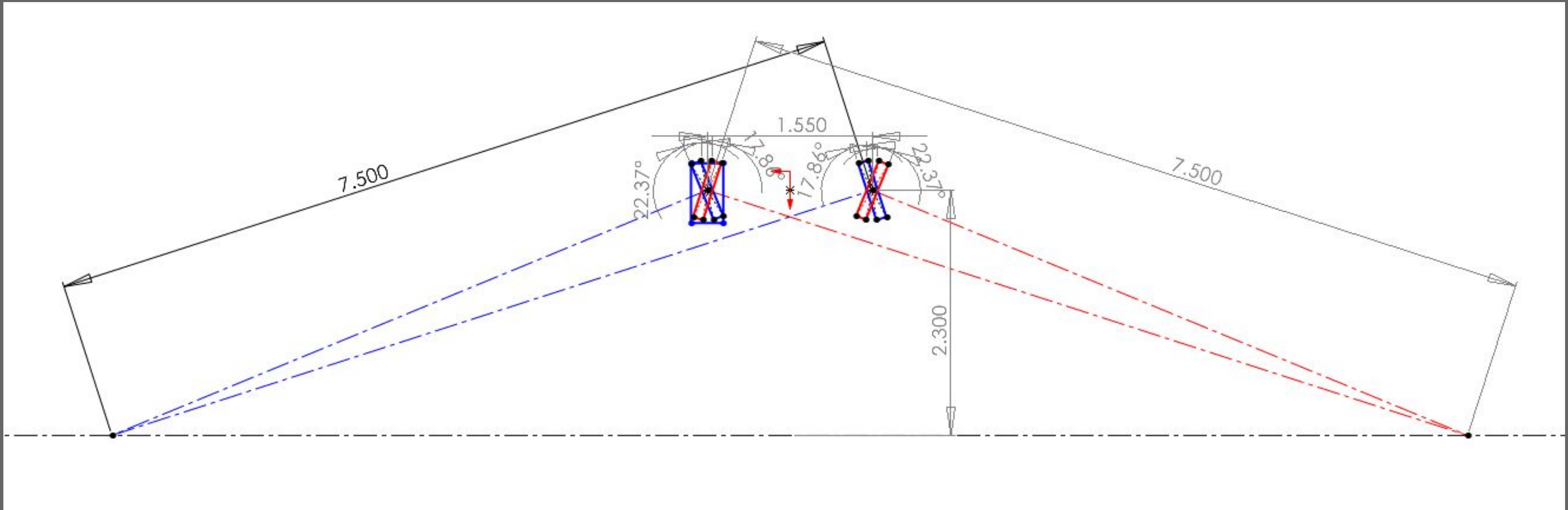
Functional Requirements + Constraints

- Ackerman Geometry
  - 7.5m turning radius
- Maintain Anti-Bump geometry
- Rigid assembly (avoiding previous vehicle issues)
  - Keep linkage as planar as possible during neutral geometry to avoid vertical force members
  - Light weight
- Keep wheel angles under 25 degrees

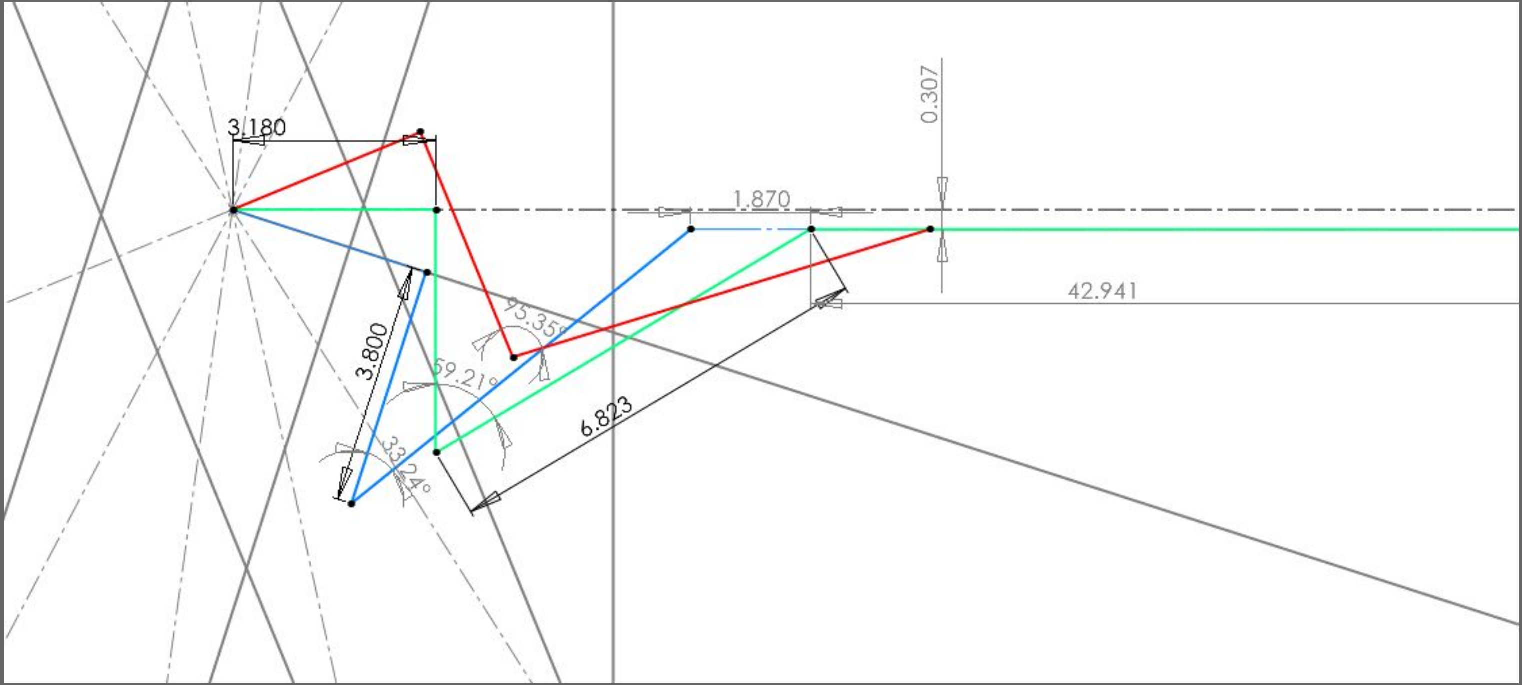
UC BERKELEY SOLAR VEHICLE TEAM

Powersketch

7.5m Turning Radius | 1.55m TW | 2.3m WB | – Max steering angles 22.4 deg and 17.9 deg < 25 deg ✓



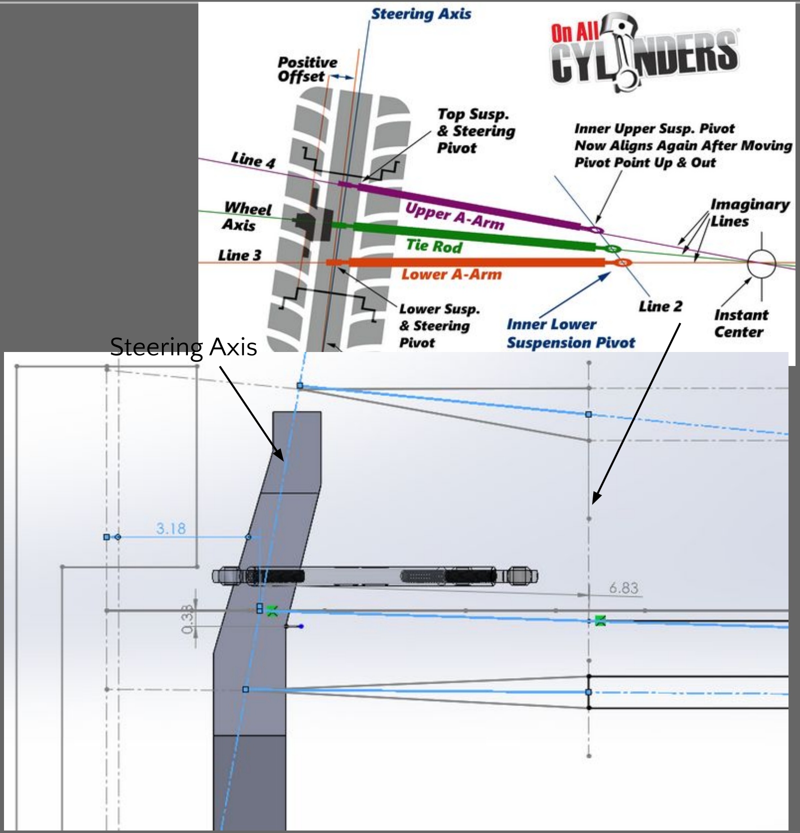
Linkage Geometry Pt 1



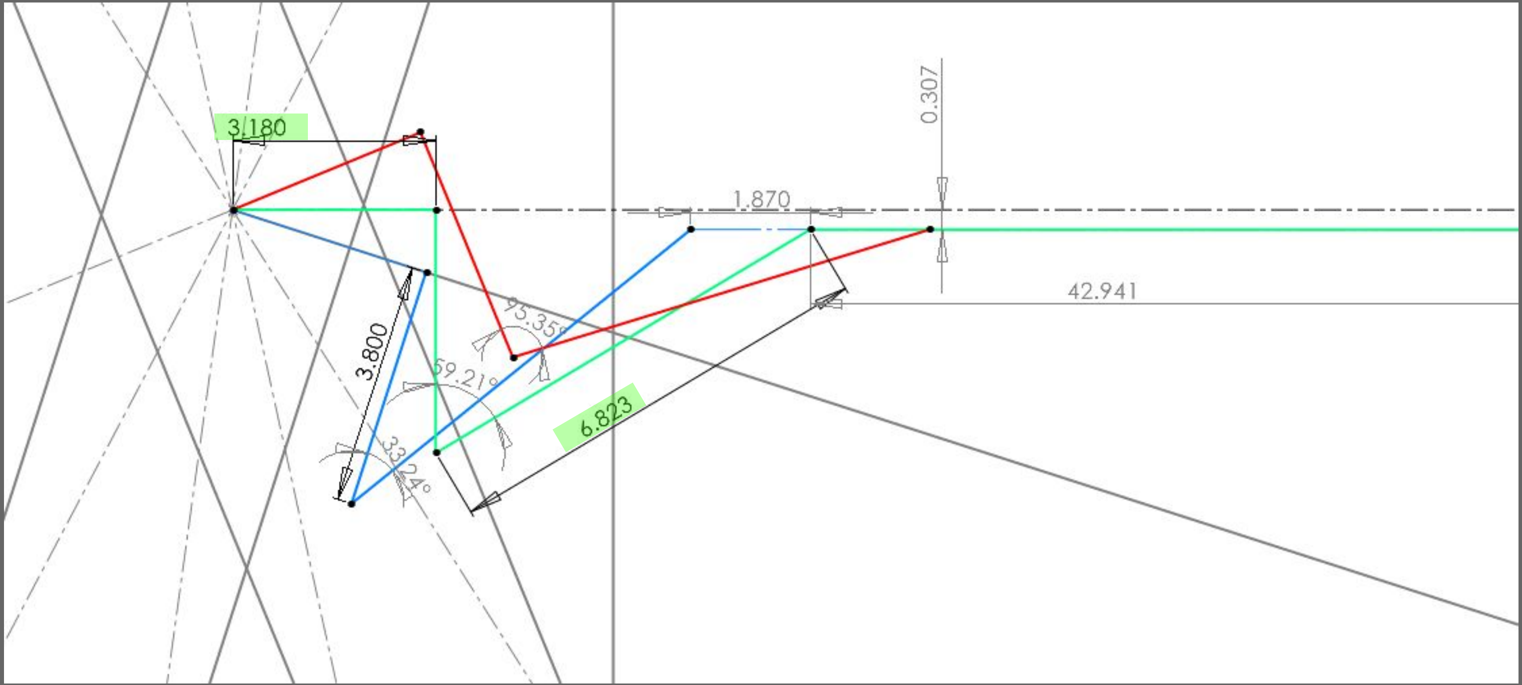
CALSOL
UC BERKELEY SOLAR VEHICLE TEAM

Linkage Geometry Pt 2

- Tie Rod Length
  - To satisfy anti-bump steering, our tie rod length restricted by front suspension a-arm geometry
  - Results in 6.83in tie rod length and defines steering knuckle tire X offset of 3.18 in



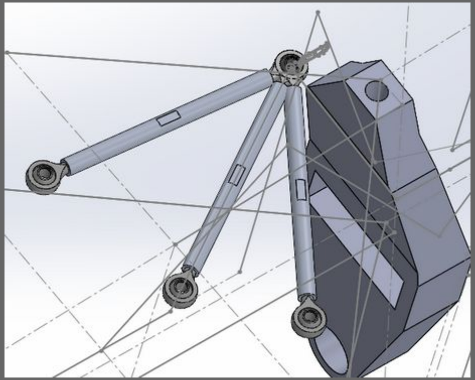
Linkage Geometry Pt 3

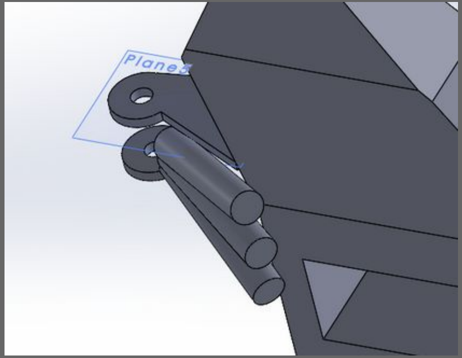


Linkage Geometry Pt 4

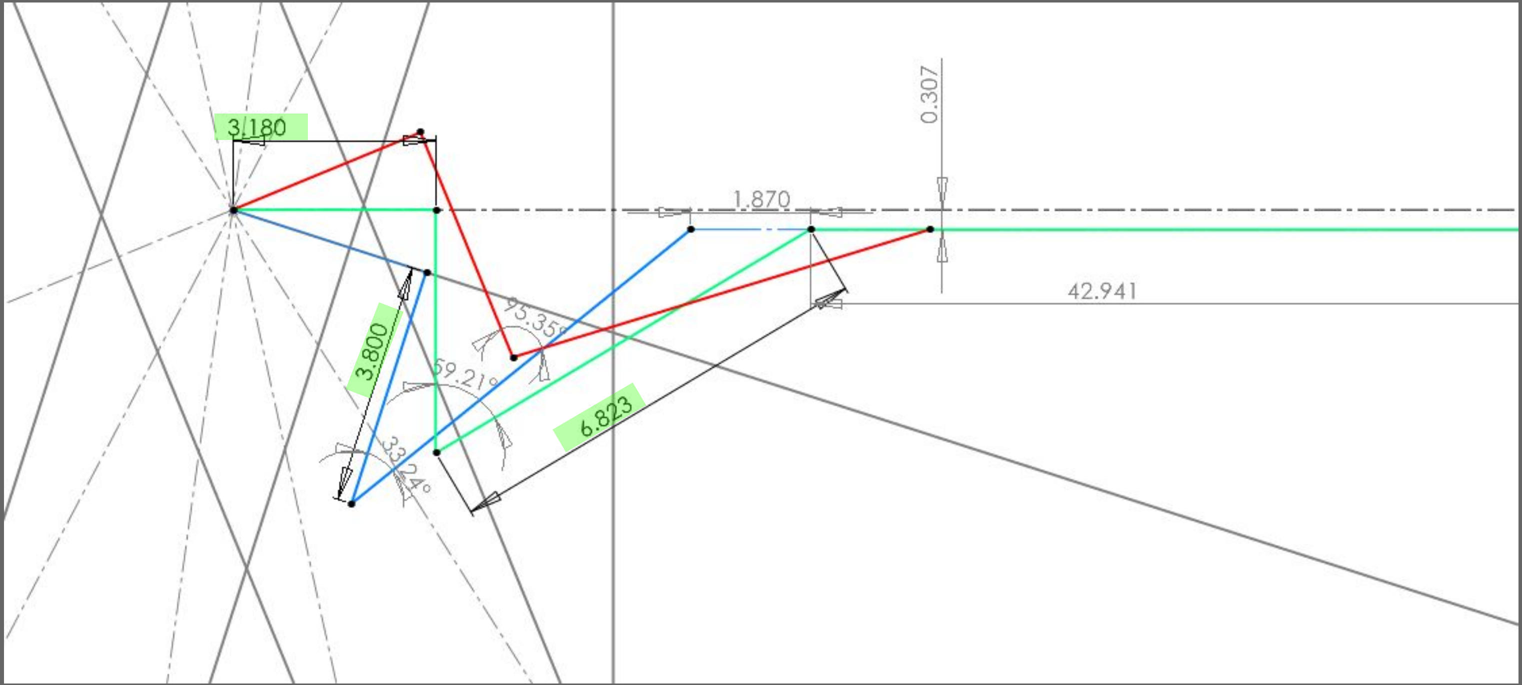
- Steering Knuckle Y offset
  - Accounting for
    - max tie rod ball swivel
    - necessary steering tie rod angles
    - never clip the upright
- Any value able 3.5 inches satisfied
- Final Y offset of 3.8in

Note : besides the additional clearance, this also reduced our rack travel the most





Linkage Geometry Pt 5



Linkage Geometry Pt 6

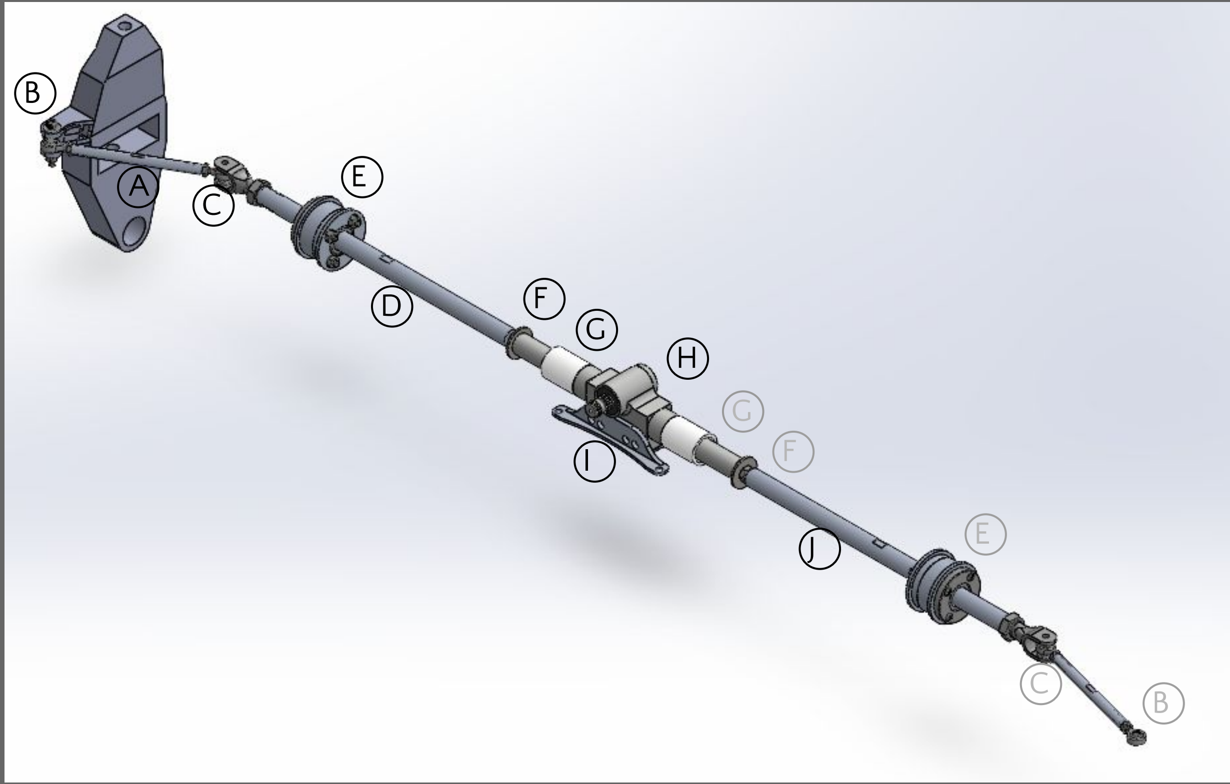
- Rest of the dimensions like the center rack length, center rack position, and rack travel were solved for by the power sketch purely by geometrical constraints
- Rack Travel 1.87 in (results in 432 deg lock to lock steering wheel)

Note: Bc of anti-bump constraints, our rack travel only allows ~432° lock-to-lock instead of desired 360°, requiring 216° per side, which we could have minimized with tighter steering-suspension integration—something crucial to prioritize in future generations.

Component Breakdown/Analysis

Master CAD of Assembly

- A – Tie Rod Assembly
- B – Steering Knuckle
- C – Clevis Rod End
- D – Left Center Rack Extension
- E – Linear Rail Inserts Assembly
- F – Custom Steering Stop Washer
- G – Steering Stop PVC
- H – Rack and Pinion
- I – Rack Mount
- J – Right Center Rack Extension



UC BERKELEY SOLAR VEHICLE TEAM

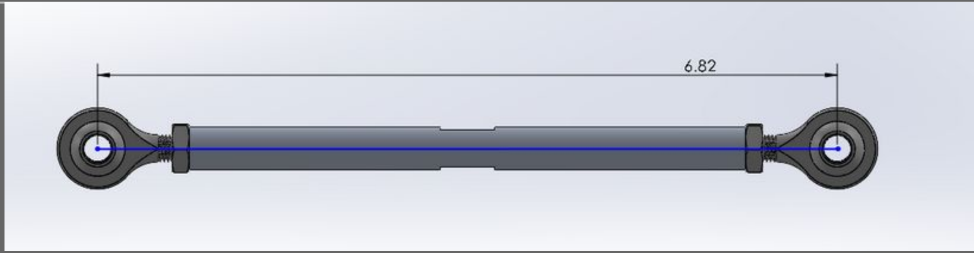
Worst Case Load Classification

- Simulating transient forces on steering quite tedious and difficult
- Instead simulate **worst case load**
  - Driver exerting entire 180 lb body weight onto steering wheel while tire pinned up against a curb
  - Spreadsheet by Han 🐐
    - Used to determine tie rod buckling FOS, forces on the tie rod, tie rod radius etc.
    - Encapsulates a lot of the hand calcs done by steering
  - For reference on how extreme this load is
    - 1G of excalibur: 3113 N
    - Magnitude of force on tie rod from this case scenario = 7878N

A - Tie Rod Assembly pt 1

[Tie Rod Detailed confluence]

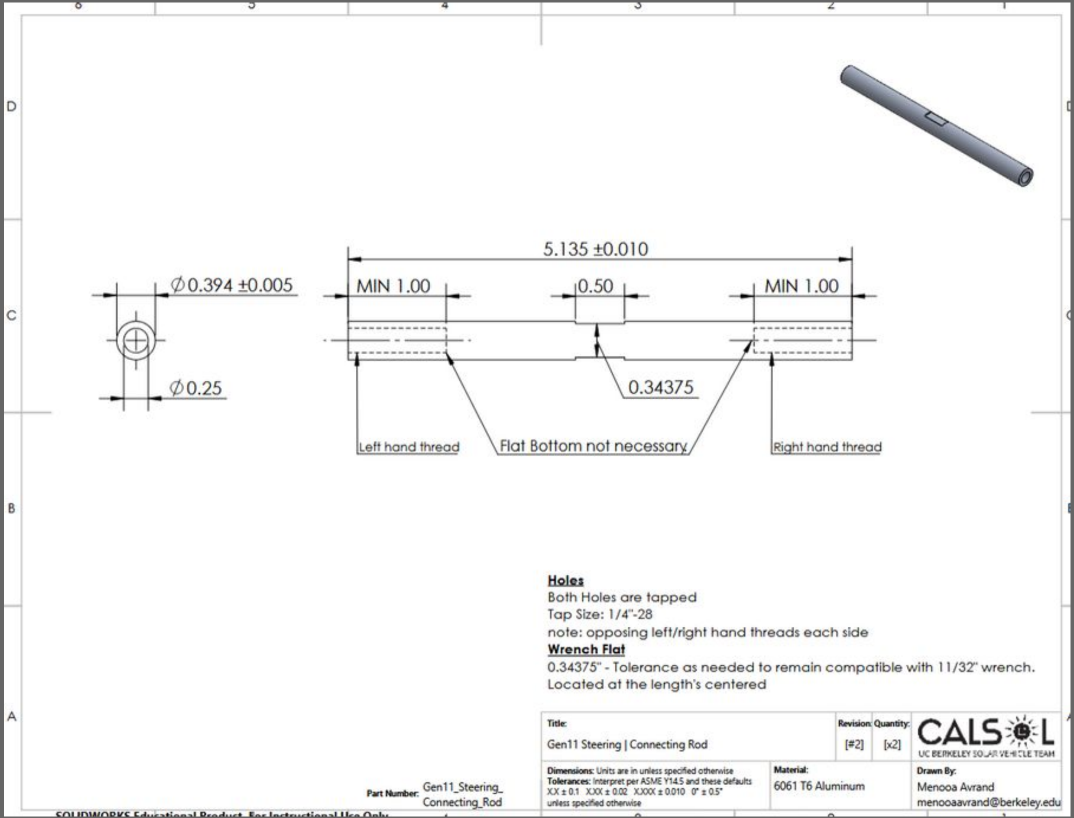
- Worst Case Load
  - Spreadsheet 0.392in diameter rod
  - Material : 6061 T6
  - FOS Tie Rod Axial : 2.75
  - FOS Tie Rod Buckling : 1.41
- Rod End
  - Load capacity of 2,800 lbs (12,455 N)
- Connecting Rod Design
  - Length of 5.697in
    - 5.135in Length
    - hex nuts (0.156 * 2)
    - 0.25 in total thread room
  - Wrench Flats
- Two complete assemblies | $55.94



Part	Quantity	Cost Per Item	Total Cost
Ball Joint Rod End, 1/4"-28 Right Hand Thread	2	$5.43	$10.86
Ball Joint Rod End, 1/4"-28 Left Hand Thread	2	$5.43	$10.86
6061 T6 Stock for Custom Connecting Rods	2 ft	$9.29	$9.29
Thin-Profile Hex Nut 1/4"-28 Thread Size Right Hand Thread	1	$7.69 per pack of 100	$7.69
Thin-Profile Hex Nut 1/4"-28 Thread Size Left Hand Thread	1	$17.24 per pack of 100	$17.24
			$55.94

A - Tie Rod Assembly pt 2

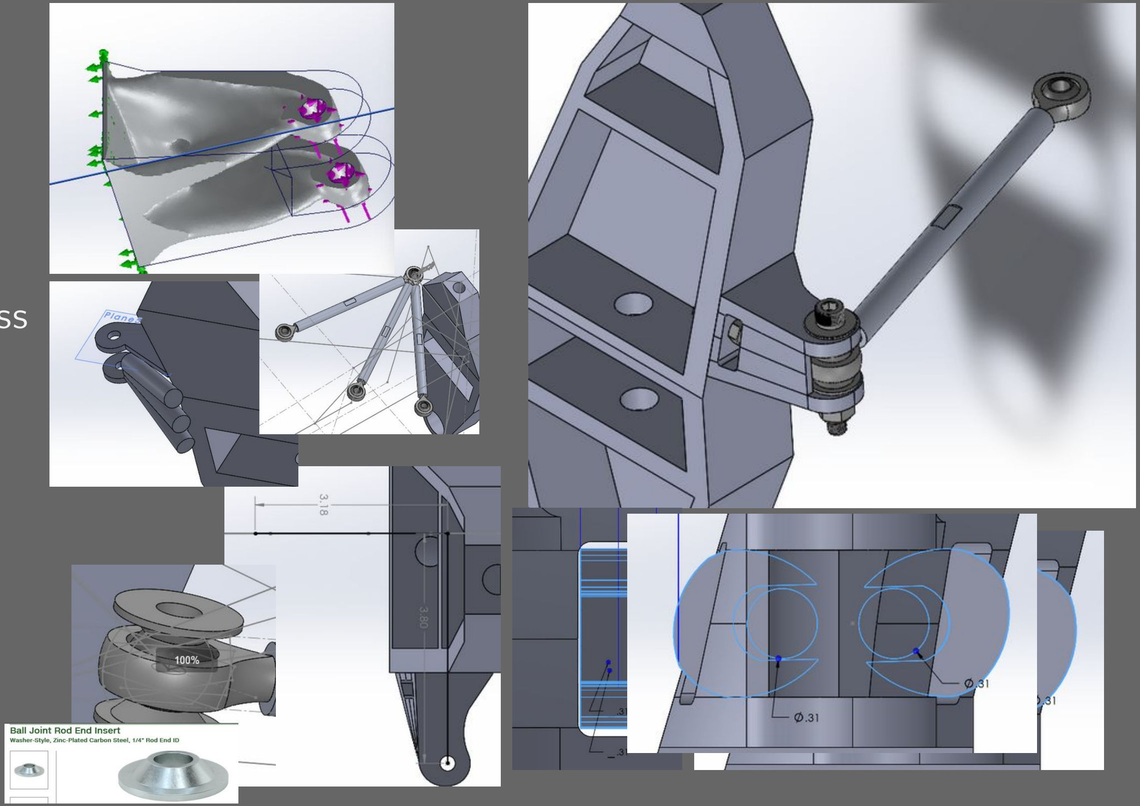
[Tie Rod Detailed confluence]



B - Steering Knuckle pt 1

[Steering Knuckle Detailed confluence]

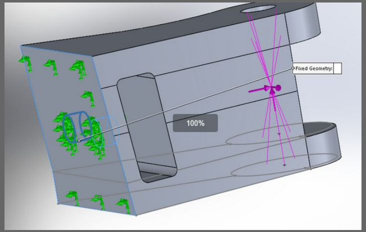
- ❖ Design initially based off a topology optimization from worst case load
- ❖ Accounts for
  - ➢ Tie rod x-y-z sweep
    - ■ 2x rod end insert thickness
  - ➢ Fits 8mm wrench for the M5 upright mounting hardware

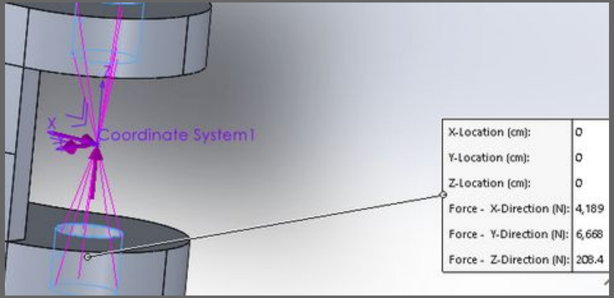


CALSOL
UC BERKELEY SOLAR VEHICLE TEAM

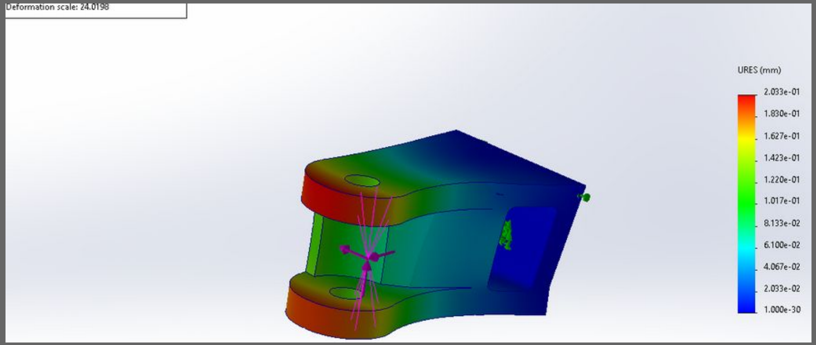
B - Steering Knuckle pt 2

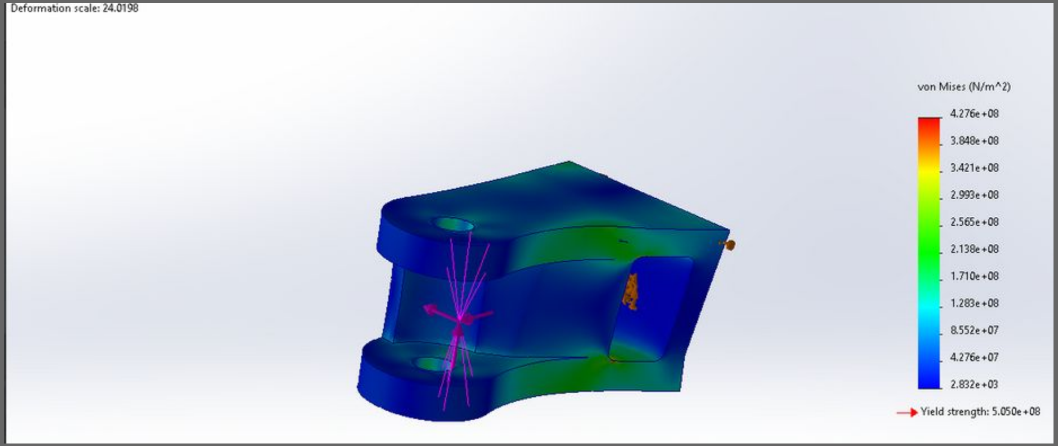
[Steering Knuckle Detailed confluence]





- Sims :)
- Material: 7075 T6
- Remote Load at Tie rod center
  - Worst Case Load – 4189 N in x | 6668N in y | 203.4N in z
- Fixed contact surface + bolt hole surfaces
- Results | Min FOS 1.2
  - Deflection of 0.2mm

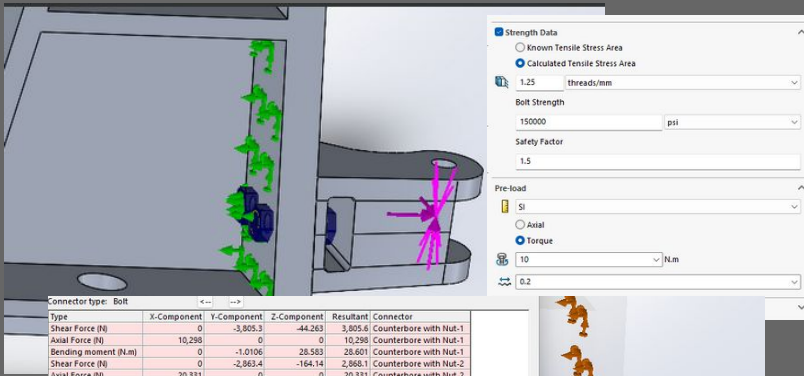


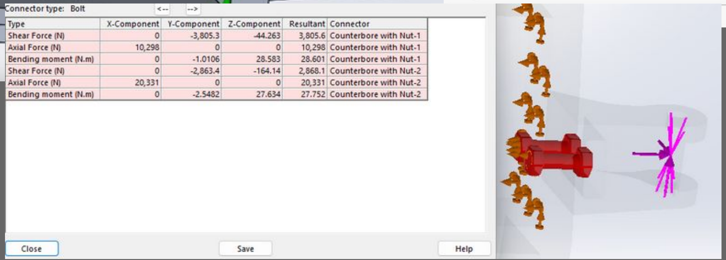


B - Steering Knuckle pt 3

[Steering Knuckle Detailed confluence]

- Bolt Sims connecting steering knuckle to upright
- Using M5 [High-Strength Class 10.9 Steel Hex Head Screws]
  - Tensile Strength 150,000 psi
  - Pre load of 10 Nm (class 10.9 max)
- Same remote load worst case
- Fix upright inner surface and contact local interaction





Connector type: Bolt

Type	X-Component	Y-Component	Z-Component	Resultant	Connector
Shear Force (N)	0	-3,805.3	-44.263	3,805.6	Counterbore with Nut-1
Axial Force (N)	10,298	0	0	10,298	Counterbore with Nut-1
Bending moment (N.m)	0	-1.0106	28.583	28.601	Counterbore with Nut-1
Shear Force (N)	0	-2,863.4	-164.14	2,868.1	Counterbore with Nut-2
Axial Force (N)	20,331	0	0	20,331	Counterbore with Nut-2
Bending moment (N.m)	0	-2.5482	27.634	27.752	Counterbore with Nut-2

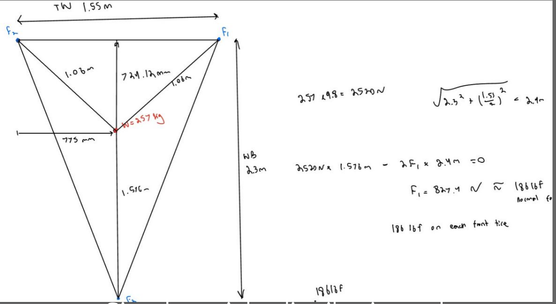
- Results
  - M5 bolts can't handle our worst case load (we need class 12.9 M8 or class 10.9 M10 bolts)
    - This is extremely overkill and our load case is too unrealistic, for reference Excalibur uses class 8.8 M4 (lower tensile strength and lower pre load rating)

CALSOL
UC BERKELEY SOLAR VEHICLE TEAM

B - Steering Knuckle pt 4

[Steering Knuckle Detailed confluence]

- Results Interpretation
  - Our worst case load is too extreme
    - Note : carbon fiber sleeve holding steering shaft at 80lbs by Clarise (we can't even exert 180lbs without that breaking)
  - Bolts at 0.15 FOS w/ 6668 in x | 4189 N in y | 203.4N in z load
    - Realistic max forces to overcome tire friction if 186lbf on tire $= -730\ \hat{i} - 458.6\,\hat{j} + 22.8\,\hat{k}$ N
      - Assuming 0.8 coefficient of friction
      - Assuming a linear system – Bolts results in 1.4 FOS



Simple weight distribution calc

C - Clevis Rod End pt 1

[Clevis Rod End Detailed confluence]

- No off-the-shelf clevis rod ends can house both the tie rod + tie rod inserts so we have to make custom ones
- Assume the tie rod is a two-force member,
  - Forces the steering knuckle experiences are similar to what the clevis will
  - Same worst case load the forces are 6668N in compression, 208N vertically and 4189N laterally.

- Running FEA with threads is pretty problematic since there are extreme sharp corners with large stress concentration so I computed the FOS manually

- Material Selection for custom thread
  - Compute bending stress on ⅝ -18 threads- 74,571 psi -------->
    - chose Easy-to-Machine 1144 Carbon Steel Rod
      - Yield Strength: 100,000 psi
  - FOS on threads= 100,000psi / 74,571 psi = 1.34

$$F_\perp = \sqrt{(208N)^2 + (4189N)^2} = 4194N \approx 942.4 \text{ lbf}$$

lever arm $x = 1.5$ in

$$M = F_\perp \cdot x = 942.4 \text{ lbf} \times 1.5 \text{ in} = 1413.6 \text{ lbf} \cdot \text{in}$$

Bending stress $\sigma = \frac{M \cdot c}{I}$

$M = 1413.6$ lbf·in

$c = d/2$

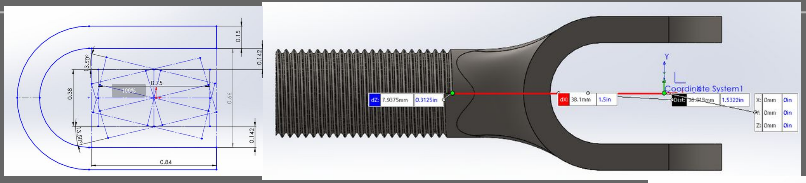
$J = \frac{\pi d^4}{64}$

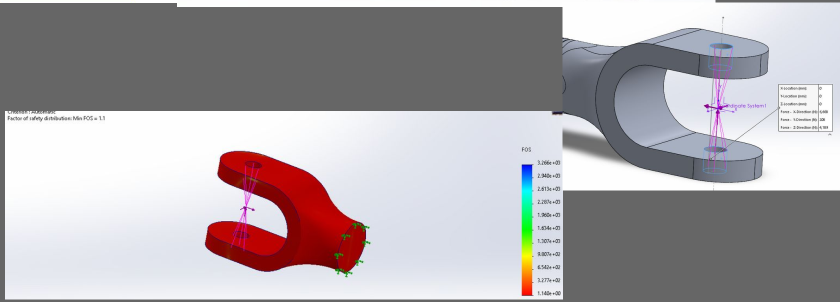
d = Minor diameter for 5/8-18 threads = 0.578 in

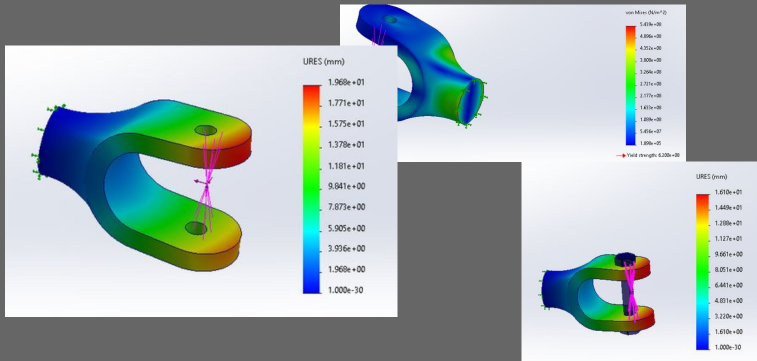
$$\sigma = \frac{M\, d/2}{\frac{\pi d^4}{64}} = \frac{32M}{\pi d^3} = \frac{32 \cdot (1413.6 \text{ lbf} \cdot \text{in})}{\pi (0.578 \text{ in})^3} = 74,571 \text{ Psi}$$

C - Clevis Rod End pt 2

[Clevis Rod End Detailed confluence]



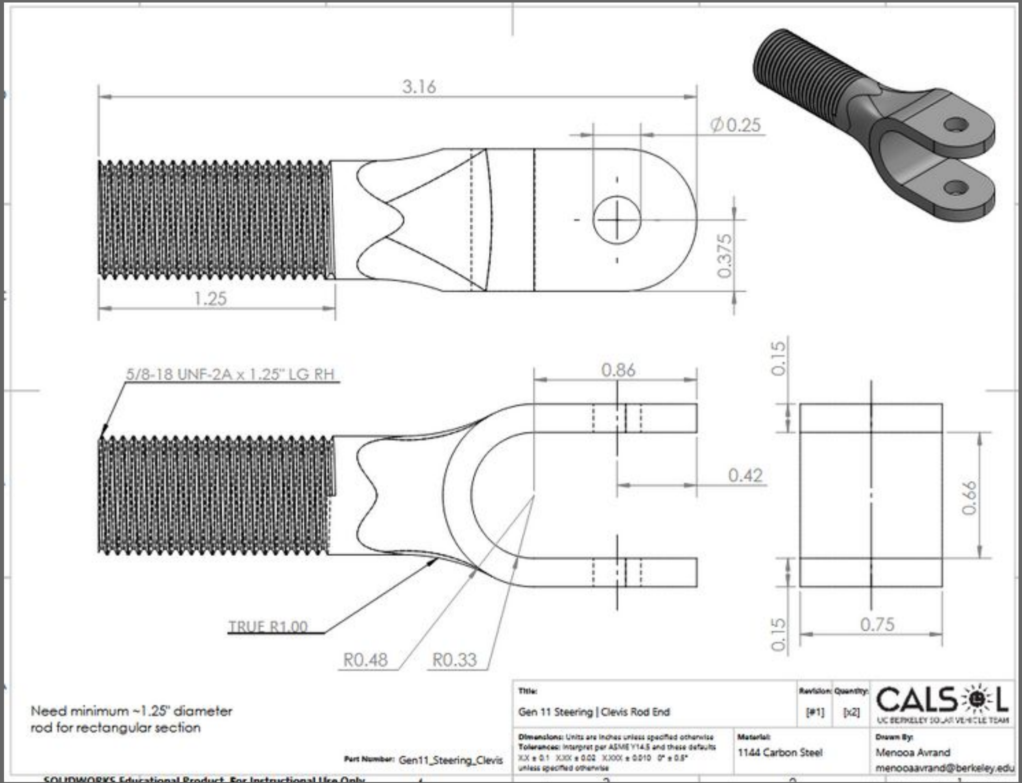




- Sims on Clevis itself
  - Material : 1144 Carbon steel
  - Remote worst case load 6668N in compression, 208N vertically and 4189N laterally
  - Fixed circular end
- Results:
  - min FOS 1.14
  - Deflection 1.9cm
    - Deflection doesn't include bolt
  - Deflection w/ bolt 1.6cm
- Takeaway: 1.14 FOS seems low but our load case is 9.12x our expected friction based driving loads: results in 10.4 FOS

C - Clevis Rod End pt 3

[Clevis Rod End Detailed confluence]



D & J - Rack Extensions pt 1

Rack Extension Detailed confluence

- Have to extend our rack and pinion so that it matches our center rack length from our power sketch.
- Center rack needs to be 43.326in total
  - Rack and pinion's neutral position is not dimensionally neutral so our extensions will accommodate for this so we have 43.326/2 = 21.663in on each side

______________ ________ ______O______ ________ ______________

15.578" 3.7635" 4.643" 3.3485" 15.993"

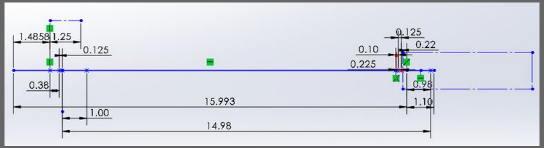
- Thus
  - L_extension_left + 3.7635" + 4.643/2 = 21.663in
    - Left extension = 15.578"
  - L_extension_right+ 3.3485" + 4.643/2 = 21.663in
    - Right extension = 15.993"

CALSOL
UC BERKELEY SOLAR VEHICLE TEAM

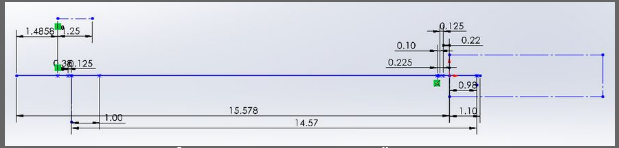
D & J - Rack Extensions pt 2

[Rack Extension Detailed confluence]

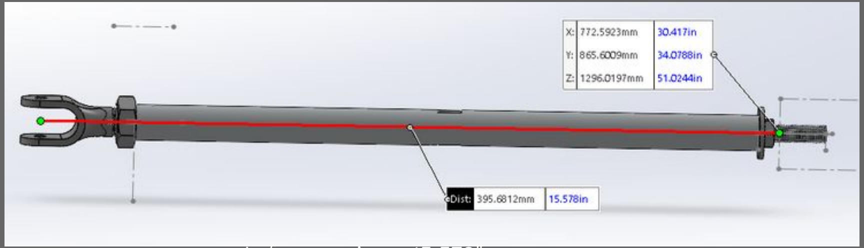
- Within our computed lengths we must account for
  - how far out the clevis offsets
  - 0.25” total thread room
  - Nut on each side
    - Grade 5, Zinc-Plated, 3/8"-24 Thread Size   Height 7/32"
    - Grade 5, Zinc-Plated, 5/8"-18 Thread Size   Height 3/8"
  - Custom steering stop washer - 0.1”



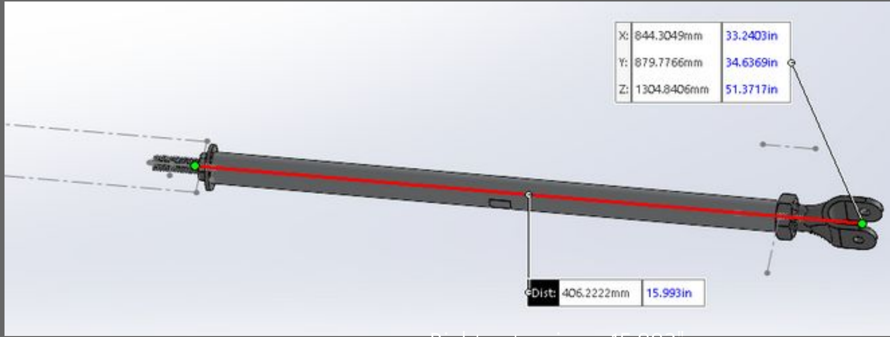
Right extension = 15.993"



Left extension = 15.578"



Left extension = 15.578"



Right extension = 15.993"

D & J - Rack Extensions pt 3

[Rack Extension Detailed confluence]

- Since we are incorporating linear rail inserts to eliminate the large moment arm the center racks make onto the rack mount (avoiding panel issues excalibur had) the rack extensions will be mainly in buckling.
- Worst case load would result in 6668 N in buckling/compression
  - Computed the minimum radius to handle buckling load
    - 0.263inches for 7075 T6
    - 0.265 in for 6061 T6
  - We need ⅝ threads for the clevis so we will be well above this
- Although 6061 passes, 7075 is a better choice - avoid galling and cross threading w/ steel interfaced parts

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \qquad I = \frac{\pi r^4}{4} \text{ for solid circle/rod}$$

$$P_{cr} = \frac{\pi^2 E \frac{\pi r^4}{4}}{(KL)^2}$$

$$\frac{4 P_{cr} (KL)^2}{\pi^3 E} = r^4$$

$$r = \left(\frac{4 P_{cr} (KL)^2}{\pi^3 E}\right)^{1/4}$$

P_{cr} critical buckling load = 6700 N

L longest extension length = 15.973" = 0.4062222 m

K Pinned - Pinned connection = 1.0

7075 - T651 $E \approx 71.9 \times 10^9$ Pa

$$r = \left(\frac{4 (6700 N)(0.4062222 m)^2}{\pi^3 (71.9 \times 10^9 Pa)}\right)^{1/4} = 0.006687$$

which is 0.26326 in

6061 - T6 $E \approx 69 \times 10^9$ Pa

$$r = \left(\frac{4 (6700 N)(0.4062222 m)^2}{\pi^3 (69 \times 10^9 Pa)}\right)^{1/4} = 0.00674$$

which is 0.26535in

Minimum radius to handle buckling load

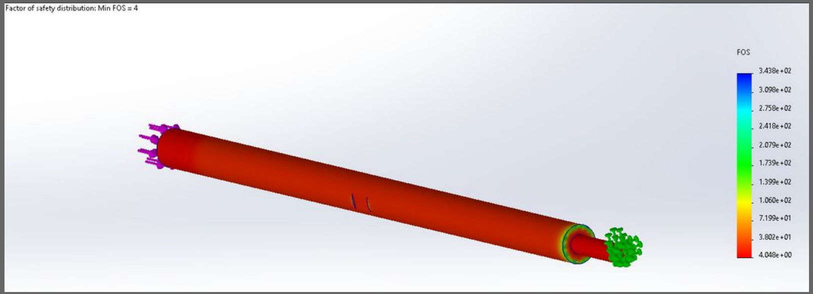
Note: steel would weigh 6.9lbs per extension, aluminum around 0.85 lbs per

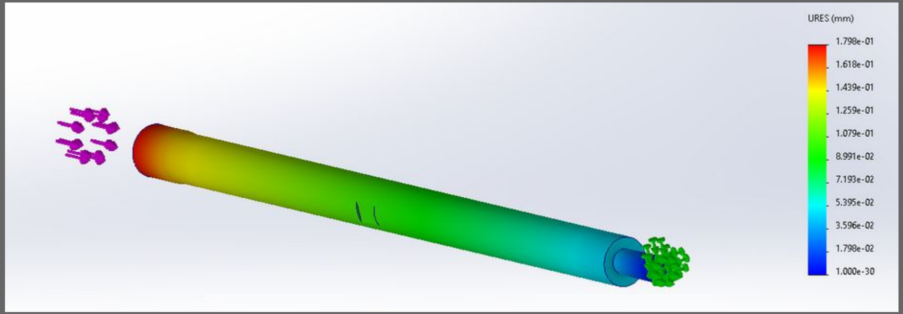
CALSOL
UC BERKELEY SOLAR VEHICLE TEAM

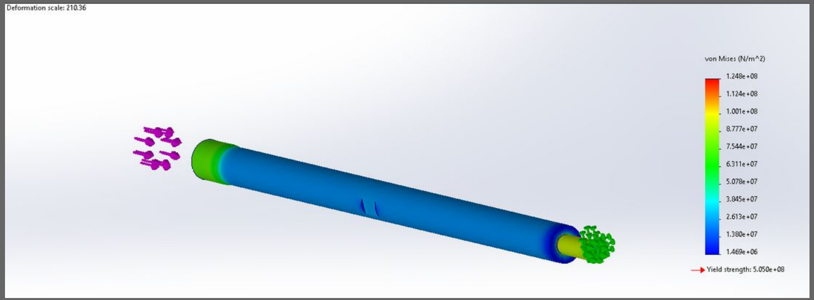
D & J - Rack Extensions pt 4

[Rack Extension Detailed confluence]

- ❖ Tested same buckling load w/ FEA (7075 T6 similar to 7075 T651 for sims)
- ❖ 6668 N compression
  - ➢ 4.0FOS
  - ➢ 0.1798 mm displacement





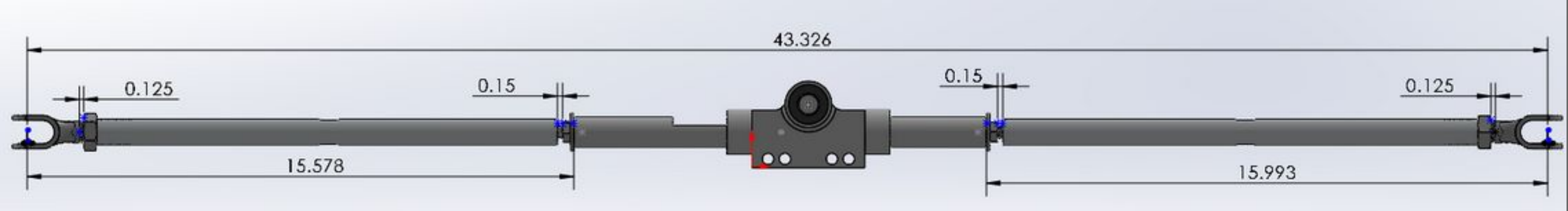


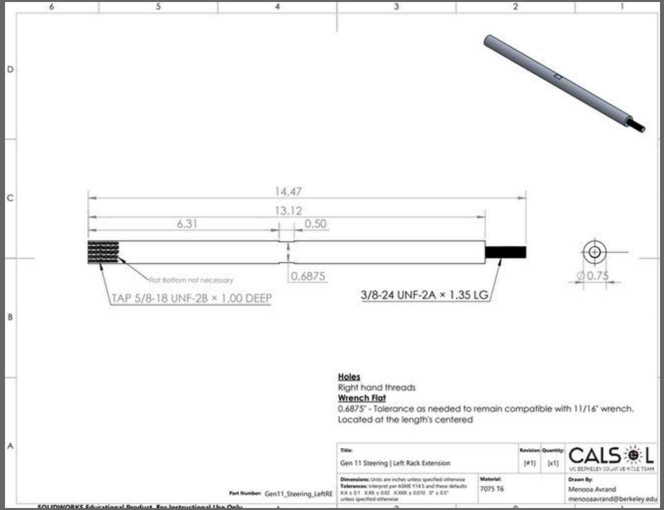
UC BERKELEY SOLAR VEHICLE TEAM

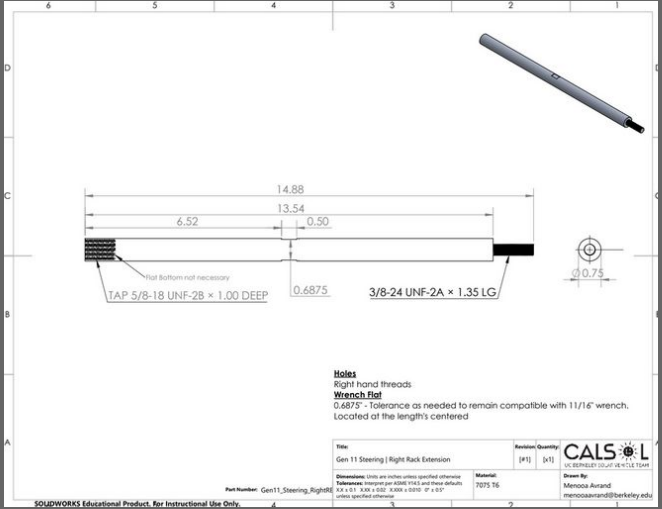
D & J - Rack Extensions pt 5

[Rack Extension Detailed confluence]

Install Guideline (closer up images on confluence linked at the top right)







F, G - Steering Stops

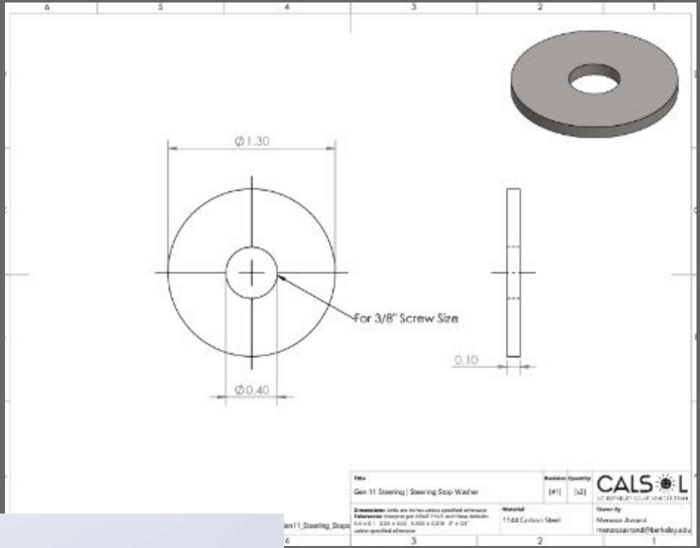
[Steering Stop Detailed confluence]

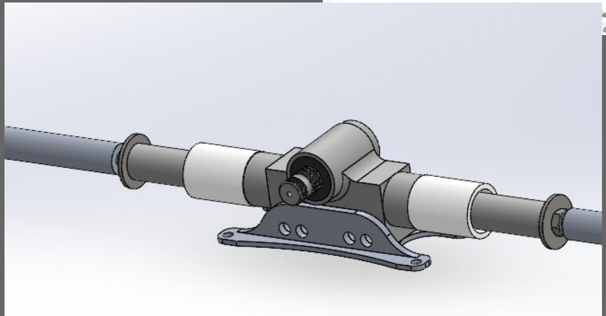
- Steering Stop Washer – Same material as knuckle (1144 steel)
  - it is 0.1" thin (very light), needs to be sturdy and reliable
- PVC steering stops
  - 1 Pipe Size
  - Used in the past, allowed by regs, lightweight and cheap
  - 1.87in rack travel = 3.74in total travel

    11.75" R&P – 4.64" = 7.11"

    7.11" /2 = 3.55" total travel both sides

    3.55" – 1.87" desired travel = 1.685" steering stops
- 1.68" steering stops





Note: We want to make these stops smaller in length since those dimensions above are the required lengths so we can turn max right and left

C, D, F, G, J BOM

[Steering Stop Detailed confluence]

UC BERKELEY SOLAR VEHICLE TEAM

- PVC Pipes
- Rack Extensions Stock
- Clevis Rod End Stock
  - Steering Stop Washer Stock (same as clevis)

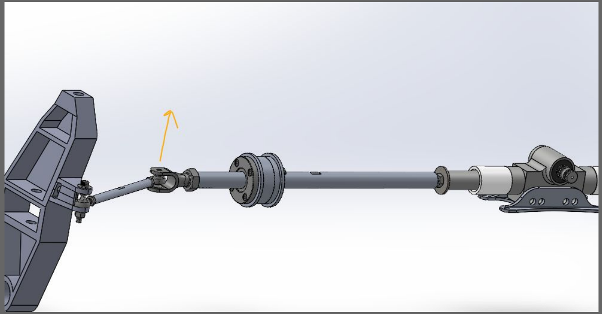
Part No.	Description	Use Case	Req. Qty.	Order Qty.	Order Qty.	Unit	Unit Price	Total
95034A100	Ball Joint Rod End Insert, Zinc-Plated, 1/4" Rod End ID	All rod ball swivel	2	4	4	Each	$6.93	$27.72
6628K44	Easy-to-Machine 1144 Carbon Steel Rod | 1 Foot | 1-1/2" Diameter	Stock for Knuckle + Washer	1 Ft	-	-	1 Ft	$32.80	$32.80
90465K67	High-Strength 7075 Aluminum Rod | 3 Foot | 3/4 Diameter	Stock for Extensions	3 Ft	-	-	3 Ft	$46.13	$46.13
48925K301	PVC Pipe 1 Pipe Size	PVC for Steering Stops (we prob have some)	3 inches	2 Feet	-	Each	$6.84	$6.84
								$113.49

E - Linear Rail pt 1

[(Info in journal - will create dedicated detailed page soon)]

CALSOL UC BERKELEY SOLAR VEHICLE TEAM

- Goal: Do not allow the center rack extension to create a massive moment onto the R&P mount
- A linear bearing that is installed onto a vertical panel using massive inserts to allow smooth rack travel and
- Typical Driving force
  - Magnitude force of 103.2lbf the linear rail must bear
  - Found one on mcmaster for $43 + compatible load capacity



There is 186lbf of force on the tire. To overcome friction, let's assume the coefficent of frictions is 0.8

Our steering knuckle from the contact patch is

sqrt (3.18in ^2 + 3..8in ^2) = 4.95in

So the torque needed at the steering knuckle to turn the wheel is

T = 186 * 0.8 * 4.95in = 736lbf-in

The Tie rod is 3.8in from the king pin axis

so our tie rod force is 736/3.8in = 194lbf = 730N î

If we assume our system is linear, then our worst case load of - 6668.7 î - 4189.7 ĵ + 208.4N k̂ N

should translate to - 730 î - 458.6 ĵ + 22.8 k̂ N

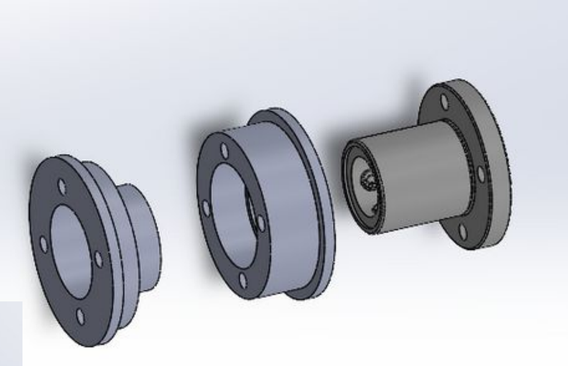
or in lbf = - 164 î - 103ĵ + 5.12 k̂ lbf

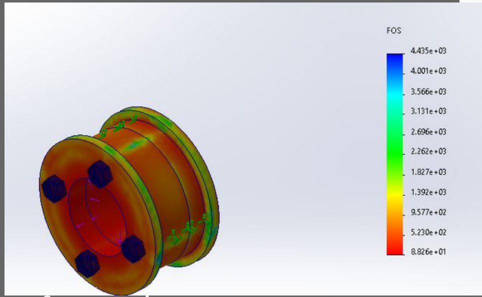
Load Capacity, lbs.	
Dynamic	190
Static	305

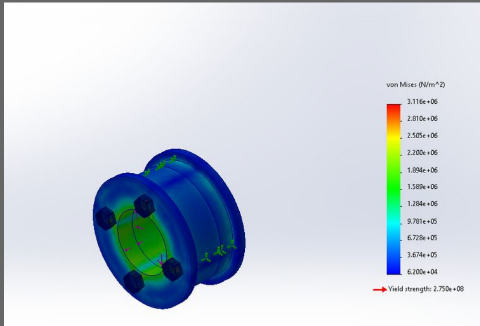
E - Linear Rail pt 2

(Info in journal - will create dedicated detailed page soon)

- Insert Assembly (haven't made drawings for this yet since panel thickness can vary through manufacturing)
  - Jackson stated we using ¼" and ½" cores
  - This vertical panel will be 1" thick to have the linear insert be as encapsulated inside a panel as possible (don't stick out on one end)
- FEA #1
  - 6061 T6 Aluminum
  - 4195N lateral/radial force
    - FOS 88
  - Don't think this sim is accurate







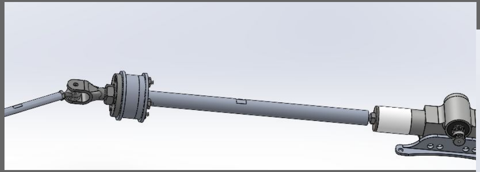
Fixture too ideal and doesn't account for moment arm from clevis/extension

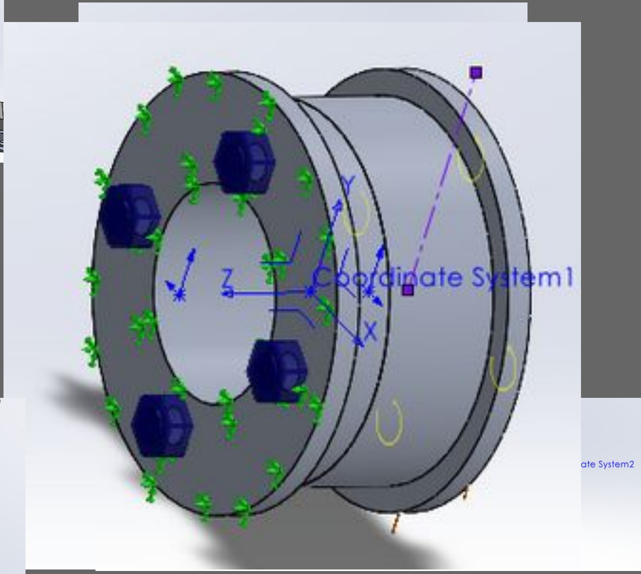
CALSOL
UC BERKELEY SOLAR VEHICLE TEAM

E - Linear Rail pt 1

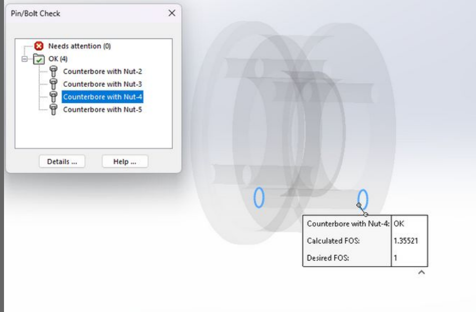
[(Info in journal - will create dedicated detailed page soon)]

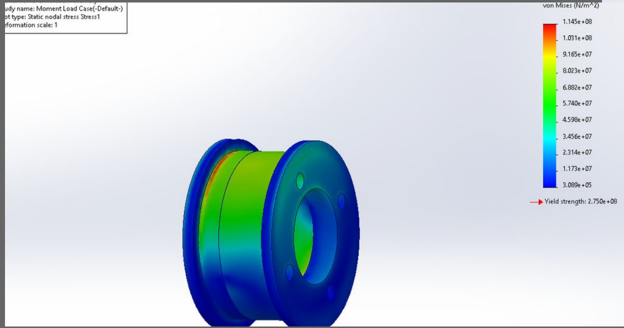
Turning Far left/right

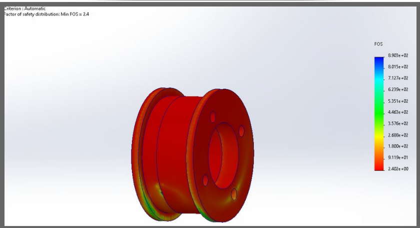




- FEA #2 Account for Moment Arm
  - 6061 T6 Aluminum
  - Remote Load 4195N 7” away
    - Creates a 5.77” moment arm but I elevated this to 7” in the sim in case vertical panel location varies and force isn’t centralized
  - Contact local interaction + class 12.9 bolts 8.45Nm preload
  - Min FOS of 2.4 on the inserts
  - Min FOS of 1.3 on bolts





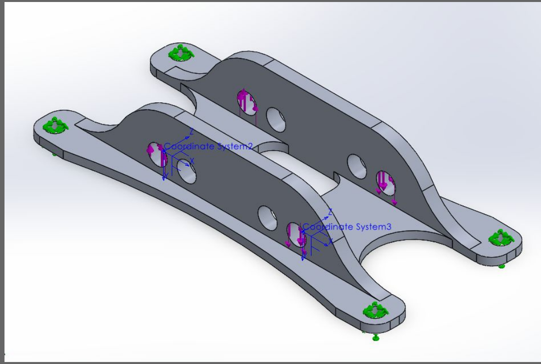


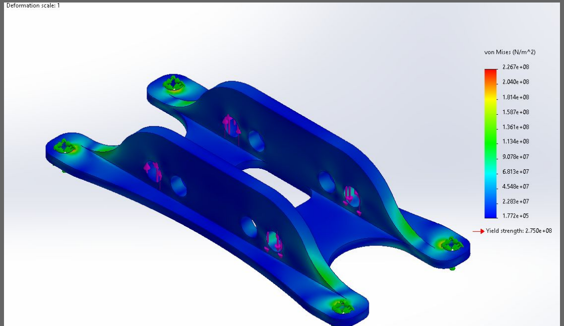
H - Rack and Pinion

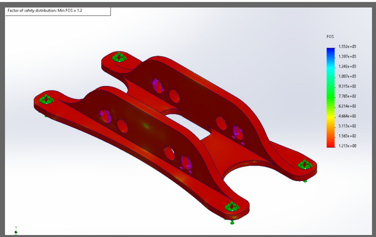
- Unused Spare Rack and Pinion from impulse
  - 5” total rack travel
  - Buggy rack and pinion
- Casted (uneven housing surfaces)
- Pinion and rack
  - Measured pinion radius by completing 1 revolution which gave us the circumference
- Saves us ~$150 not having to buy a new one

I - Rack and Pinion Mount pt 1

- Missing some R&P dimensions to finalize the mount completely
  - Mainly center rack height which will affect bolt location in the y direction (away from floor)
- FEA #1 Moment due to non planar linkages
  - 6061 T6
  - Worst case load translates to 2100Nm at center of R&P (from spreadsheet)
    - Opposing 2100N bearing loads
    - Assumes linear inserts are doing nothing (fail safe)
  - Results:
    - FOS 1.2
    - Displacement 0.084mm

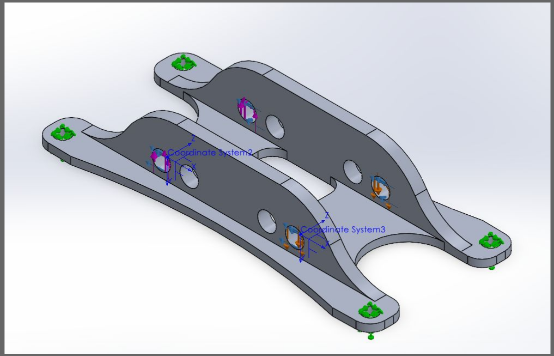


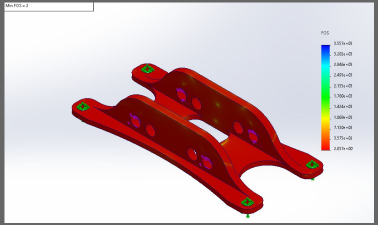


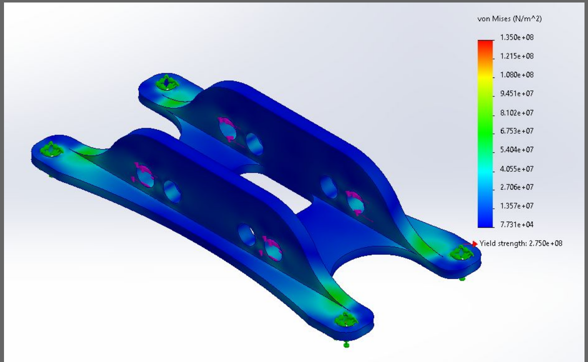


I - Rack and Pinion Mount pt 2

- FEA #2 “Buckling” force
  - 6061 T6
  - Loads
    - Worst case load translates to 2100Nm at center of R&P
      - Opposing 2100N bearing loads
      - Assumes linear inserts are doing nothing (fail safe)
    - 6669N along the center rack
  - Results:
    - FOS 2.03
    - Displacement 0.0256mm

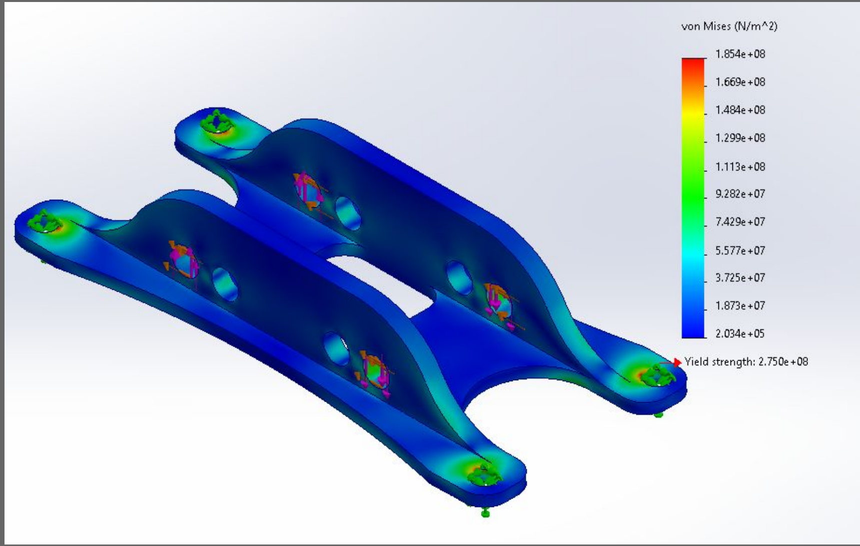






I - Rack and Pinion Mount pt 3

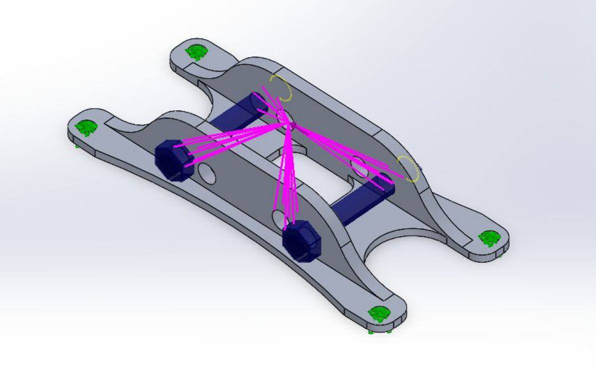
- FEA #3
  - Ran a combination of both the buckling and moment loads at the same time to see how it performs with a combined moment + force load
  - Results
    - 1.5 FOS
    - 0.07mm displacement

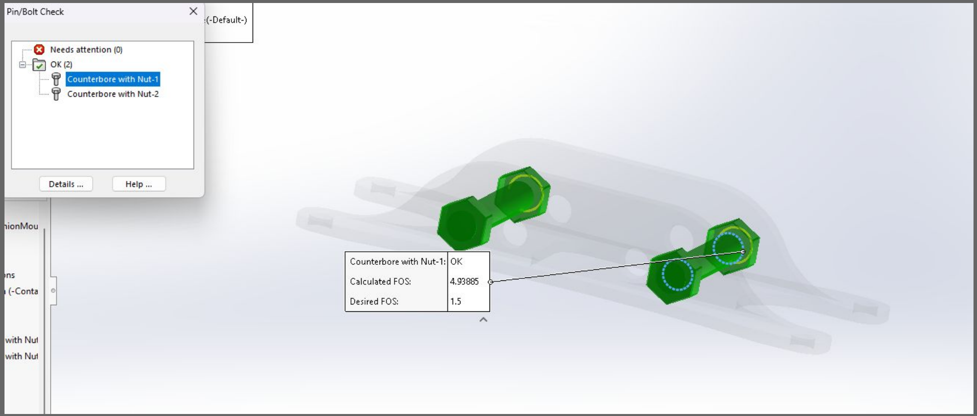


UC BERKELEY SOLAR VEHICLE TEAM

I - Rack and Pinion Mount pt 4

- FEA #4 – Rack Bolt Connection Sim
  - 5/16" bolts 170,000 psi
  - ASTM A574 equivalent to grade 8 = 21 Nm max preload but we will do 10Nm preload. Over tightening will cause the mount to compress
  - 6669N remote load simulating "buckling" force onto R&P
    - Min bolt FOS 4.9

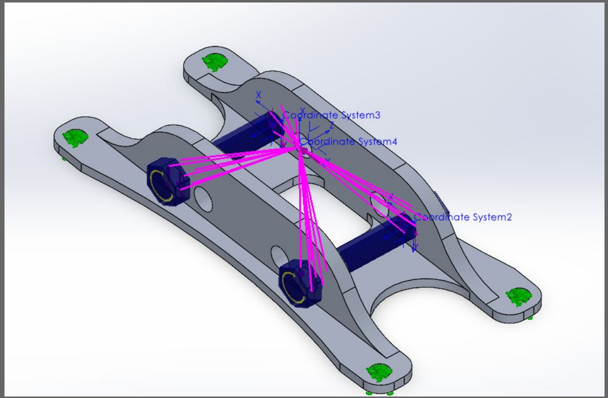


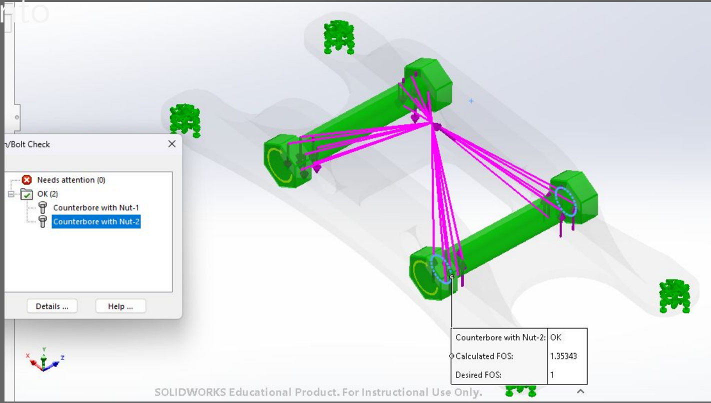


Note: After 3D printing, and making sure all holes line up w/ casted R&P, can consider removing the two additional bolt holes since we don't particularly need as our sims show. (any thoughts on this?)

I - Rack and Pinion Mount pt 4

- FEA #5 – Rack Bolt Connection Sim
  - 5/16” bolts 170,000 psi
  - ASTM A574 equivalent to grade 8 = 21 Nm max preload but we will do 10Nm preload. Over tightening will cause the mount to compress
  - Loads
    - 6669N remote load simulating “buckling” force onto R&P
    - And 2100Nm moment on R&P
  - Results
    - Min bolt FOS 1.35





Next Steps

UC BERKELEY SOLAR VEHICLE TEAM

Remaining Tasks

- Determine bolt for clevis rod end (simple bolt calc/sim to ensure it can hold up to worst case load)
- Steering Knuckle | Engr Drawing - Mirrored orientation - msg ME shop
- Move wrench flat location on rack extension towards R&P side
- Once I obtain final R&P dimensions needed
  - Finalize R&P mount
    - 3D print the mount to ensure it fits well w/ uneven casted R&P before machining
    - Sim mounting bolt holes + inserts needed for install
  - Give chassis the desired floor panel z-height based on center rack offset from R&P mount
  - Speak further w/ chassis about 1" thick panel for linear rail insert
- Comprehensive BOM including all stock and hardware